(the accelerator of)

MYRRHA in a European Context

Alex C. MUELLER
National Institute for Nuclear and Particle Physics

- apologies for my limited attendence to workshop

CNRS-IN2P3 Strategy on ADS

CNRS IN2P3 Institut National de Physique Nucléaire et de Physique des Particules

- While Nuclear Policy is (luckily?) a national prerogative, France is also part of "European Context"
- In the framework of the French legislation on Nuclear Waste, we have chosen to focus on 2 axis of research, destined to minimize high-level toxic waste, in particular with regard to minor actinides (MA):
  - Accelerator-Driven Systems (ADS) deployed as second stratum for MA transmutation coming from present and future pressurized water reactors (LWR, Gen. II, Gen. III)
  - Developpement of a Thorium-based fuel cycle with view of deployment in molten salt reactors (MSR)
- This strategy is deployed in a coherent way since more than 15 years in different scientific departments and laboratories of CNRS. IN2P3, provides and coordinates the majority of resources

Elements and coherence of our scientific approach

IN2P3 Institut National de Physique Nucléaire et de Physique des Particules

- **CNRS-IN2P3 has the ambition to be a major actor for the development of those ADS components in which it has expertise:**
    - the high-power linear accelerator (LINAC)
    - the spallation target and the beam-line to it
    - the sub-critical core and the associated reactor physics
- **CNRS-IN2P3 has coordinated the reference design for the ADS-linac, has designed and supervised construction of the target of MEGAPIE, and initiated with CEA the MUSE coupling experiment**
    - coordination of accelerator WP of EUROTRANS (construction and test of critical components partly in real scale)
    - construction of critical target components
    - construction of the GENEPI accelerator
- **CNRS considers end of 2009 as major milestone**
    - conclusions of EUROTRANS and results of PIE-MEGAPIE available to the Central Design Team (CDT) at Mol
    - GUINEVERE experiment operational
- **CNRS is organised for the 2012 date of the French law**
    - large amount of date from GUINEVERE collected and analysed
    - Central Design Team's work permits to launch ADS-demonstrator MYRRHA

National and international Collaborations

- **National:**
  - Priviledged Partnership with CEA or AREVA (F) within PDS-XADS, MEGAPIE, EUROTRANS et CDT
  - "Pole Accélérateurs" CEA-DSM / CNRS-IN2P3

- **International:**
  - Priviledged partnership with SCK-CEN Mol (B)
  - accelerators: "hard core" : INFN (I), U Frankfurt (D), IBA (B), ITN (P),
    associated with AREVA (D), ANSALDO (I),
    UP Madrid (Esp), Empresarios Agrupados (Esp), UNED (Esp)
  - MEGAPIE: PSI (CH), FZK (D), ENEA(I), JAEA(JP), KAERI (Ko), DOE (US)
  - . EUROTRANS: more than 40 partners
  - CDT : 18 partners

- **CNRS is thus in a strong partnership with the all actors of ADS nuclear research in Europe, (even world-wide). Member of the steering committees, and work-package leader**

TWG: a European ADS Roadmap

A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration

April 2001

The European Technical Working Group on ADS

The European Technical Working Group (members see below) issued in 2001 a Roadmap for Developing ADS (see left), with the propasal for a 100 MWth demonstrator.

- **Carlo Rubbia** – ENEA, Italy, Chair
- **Hamid Ait Abderrahim** – SCK-CEN, Belgium
- **Mikael Börnberg** – VTT, Finland
- **Bernard Carluec** – Framatome ANP, France
- **Guiseppe Gherardi**, – ENEA, Italy
- **Enrique Gonzalez Romero** – CIEMAT, Spain
- **Waclaw Gudowski** – Royal Institute, Sweden
- **Gerhard Heusener** – FZK, Germany
- **Helmut Leeb** – Atominstitut, Austria
- **Werner von Lensa** – FZJ, Germany
- **Joseph Magill** – JRC, European Union
- **José Martinez-Val** – Madrid Polytech, Spain
- **Stefano Monti**, – ENEA, Italy
- **Alex C. Mueller** – CNRS-IN2P3, France
- **Marco Napolitano** – INFN, Italy
- **Angel Pérez-Navarro** – LAESA, Spain
- **Massimo Salvatores** – CEA, France
- **José Carvalho Soares** – ITN Lisboa, Portugal
- **Jean-Baptiste Thomas** – CEA, France

TWG Report: Roadmap & Cost estimate

Table 2.3. Time schedule and milestones for the development of ADS technology in Europe

Year 2000+	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	25	30	40	50
Phase-1 XADS/XADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■												
Choices of Options	■	■	■	■																				
Preliminary design			■	■																				
Design + Licensing					■	■	■	■	■															
Construction								■	■	■	■	■												
Low power testing													■	■										
Full power testing														■										
XADS Operation															■	■	■	■	■	□				
XADT Conversion																	■	■	■					
XADT Operation																				■	■	■	■	
Phase-2 Prototype ADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Constr., Operation																				■	■	■	■	■
Phase-3																								
Industr. Application																								■

Roadmap for the 100 MW_{th} demonstrator (left) and budget estimates (below).

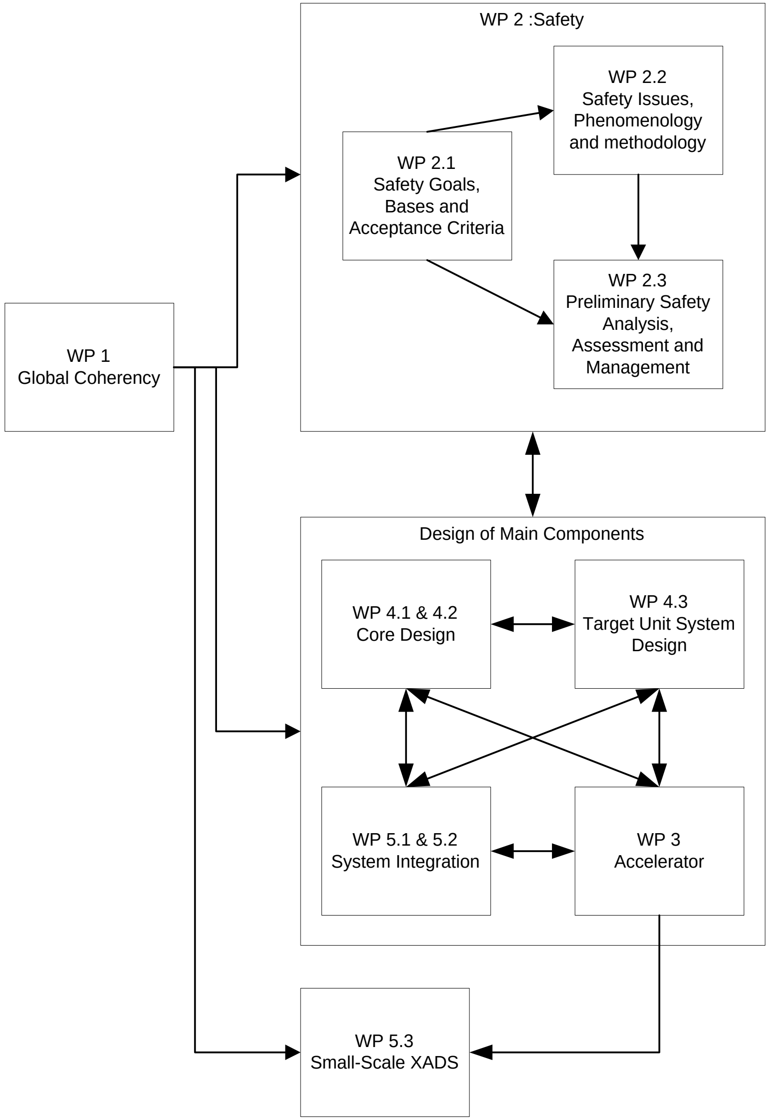
A TWG subgroup elaborated the project PDS-XADS (see next slide) which was funded by the EU.

Table 2. Estimated costs (M€) for the development of a 100 MW_{th} accelerator driven system

Year 2000+	1	2	3	4	5	6	7	8	9	10	11	12	Total
	5th FP		6th FP				7th FP						
Basic & Support R&D	30		90				70				10		200
Engineering Design	5		75				60				10		150
Construction	0		80				300				70		450
Fuel	0		10				120				50		180
Total	**35**		**255**				**550**				**140**		**980**
R&D for Dedicated Fuel	5		70				70				35		180*

* Estimated cost to 2012 for development of dedicated fuel & fuel processing

FP5 PDS-XADS*: Working Packages



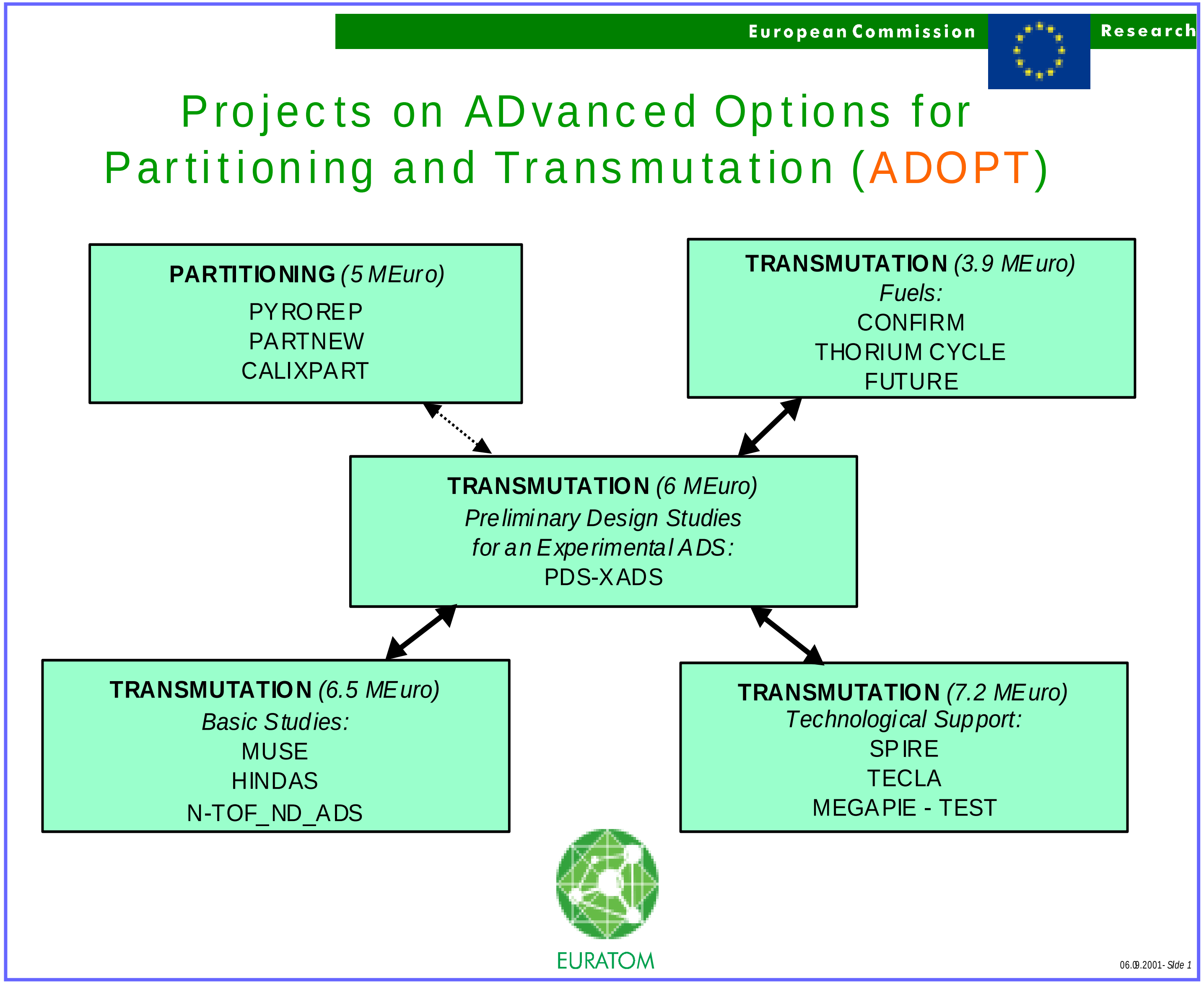
*Contract N° FIKW-CT-2001-00179 (2001-2004)

A collaboration between Industrial Partners and Research Organisations

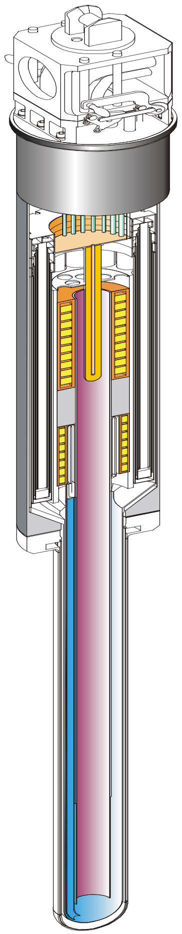
F: Framatome-F CNRS CEA
I: Ansaldo INFN ENEA CRS4
RFA: Framatome-D FZK FZJ UFra
Esp: CIEMAT Empresarios UPM
B: SCK IBA Tractebel
UK: NNC BNFL
Pt: ITN
S: KTH
Sui: PSI
Pl: UMM
NL: NRJ
Eur: JRC

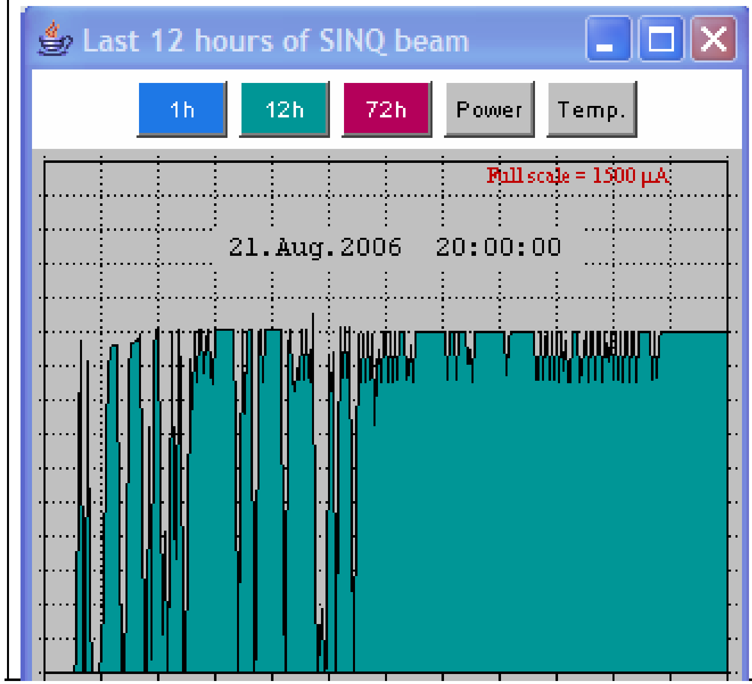
coordinateur général : Framatome (B.Carluec, B.Giraud)
coordinateur accélérateurs: CNRS-IN2P3 (A.C. Mueller)

2001-2004: PDS-XADS as central P&T project



2006: Succes of the Megapie experiment at PSI





Start of Normal User operation.

Normal user operation was started on August 21st around 8:30 and is planned to continue until the normal annual winter shut-down starting on December 23rd 2006.

The first 12 hours of proton beam is seen to the left.

The PDS-XADS Accelerator Group (WP3)

WP3 partners

- Coordinator: CNRS-IN2P3 (F)
- Participants: Ansaldo (I), CEA (F), ENEA (I), FANP (F), F GmbH (D), IBA (B), INFN (D), ITN (Pt), U. Frankfurt (D)

Main WP3 objectives

- Investigation of linac and cyclotron types with the main emphasis on the XADS requirements
- Examination of the XADS accelerator characteristics: reliability, availability, stability, power control & maintainability
- Definition of the R&D needs
- Choice of the reference accelerator type for XADS and for a long-term extrapolated industrial transmuter
- Definition of the road mapping of the ADS-class accelerators

6 Deliverables

- D9 – D47 – D48 – D57 – D63 – D80

XADS Accelerator Requirements

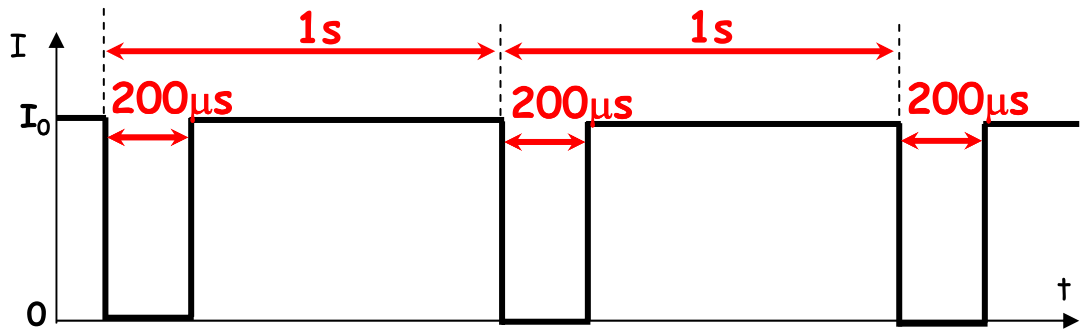
Proton Beam Specifications

- Defined by WP1
- **600 MeV, 6 mA max.** for operation
- 10 mA for the demonstration of concept
- 350 MeV for the smaller scale XADS MYRRHA
- **High reliability requirement**: less than 5 beam trips > 1 sec per year

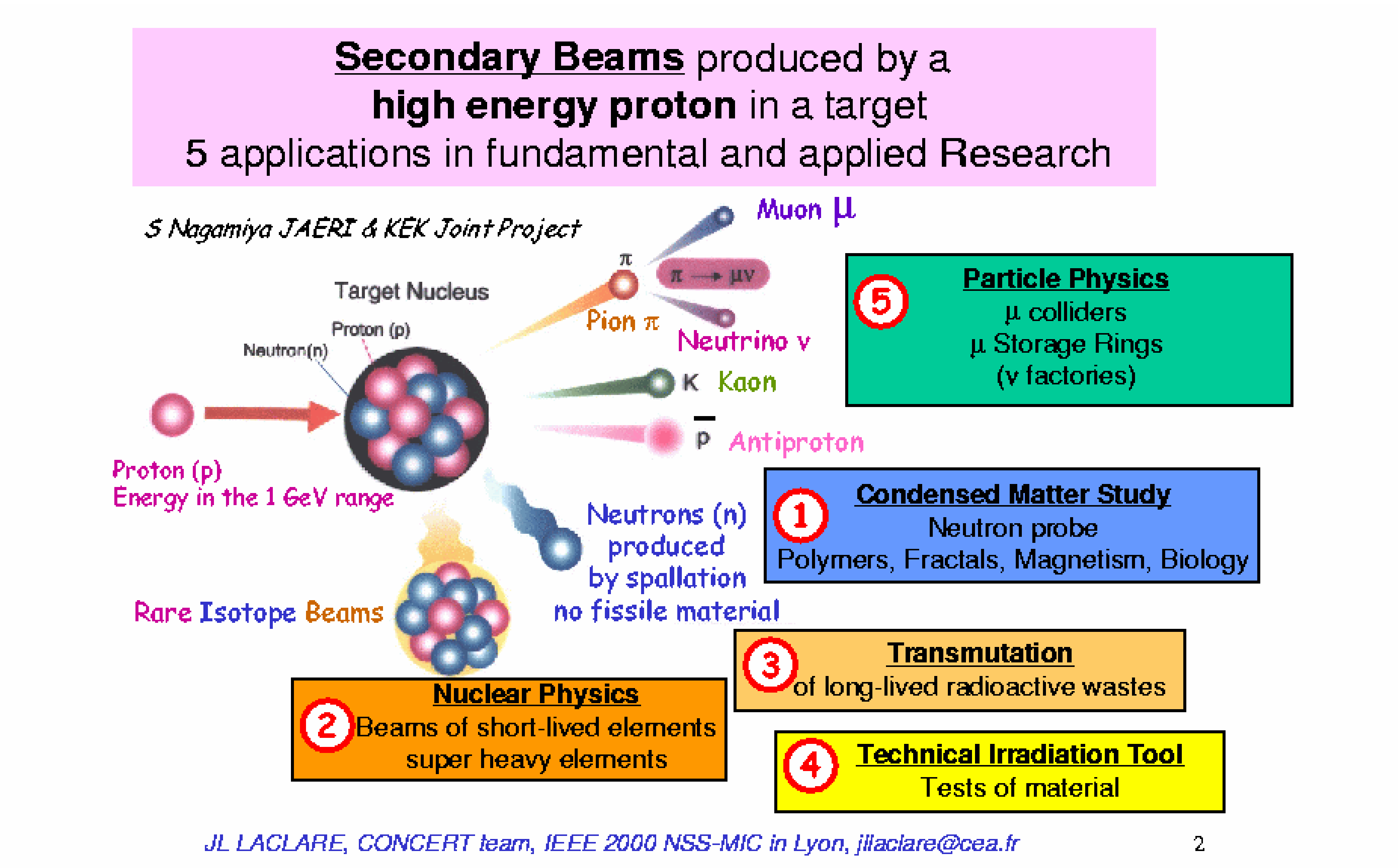
Accelerator requirements	
Max. Beam Intensity	6 mA
Proton Energy	600 MeV
Beam entry	To be defined
Beam trip number	Less than 5 per year for the accelerator design Less than 50 per year for the reactor design
Beam type	CW, best solution Pulsed, back-up solution
Beam power stability	± 2 %;
Beam energy stability	± 1 %;
Beam intensity stability	± 2 %;
Beam footprint dimensions	± 10 %.

Additional requirements

- 200 µs beam « holes » for on-line sub-criticality measurements
- Safety grade shutdown



Spallation makes secondary particles for many domains



Specifications for different HPPA

HPPA = High Power Proton Accelerator

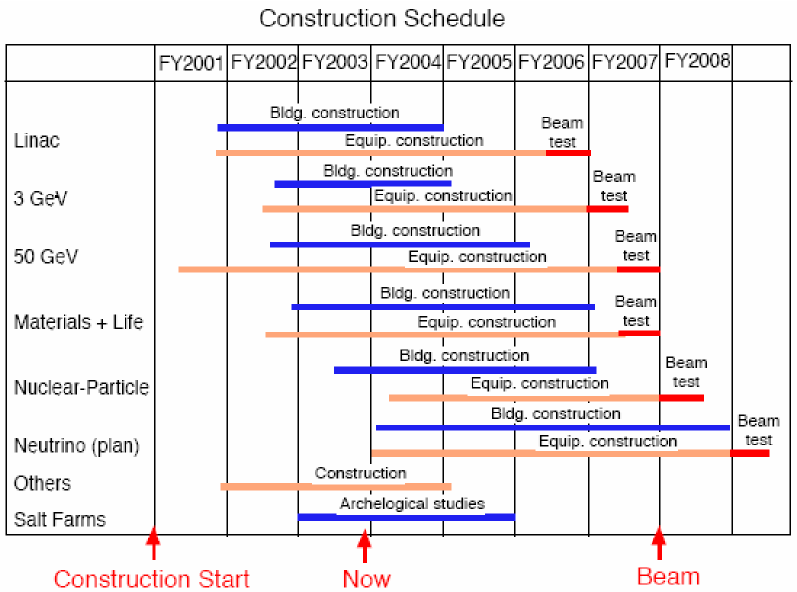
>1

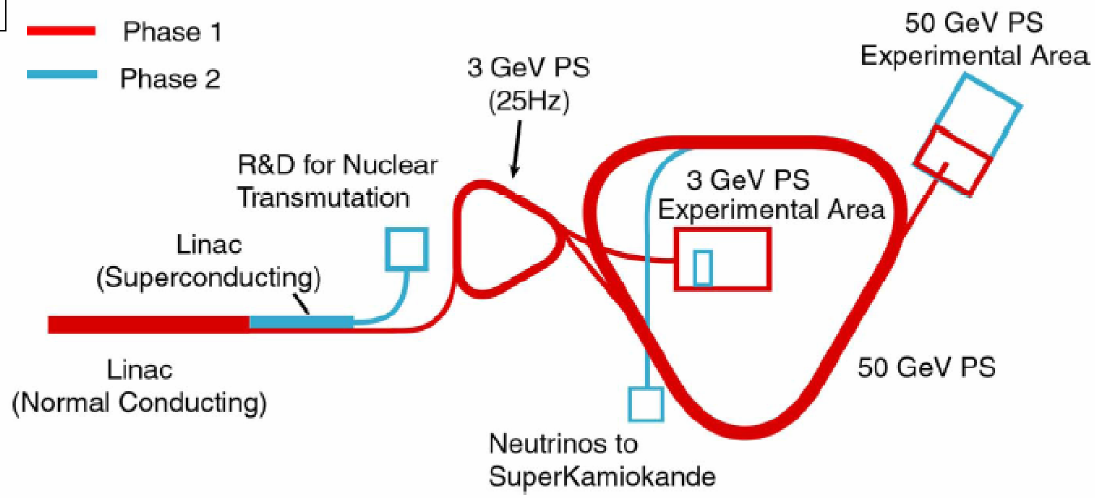
		Puissance [MW]	Énergie [GeV]
Faisceaux secondaires	Neutrinos, muons	4	2
Ions radioactifs	avec des protons avec des neutrons	.2 5	>.2 1
Irradiation des matériaux	par spallation par break-up ("IFMIF")	10 2 × 5.4	1 .04
Matière condensée	avec des neutrons	5	1.3
Transmutation	Démo 100 MW thermique Système industriel	5 10 à 20	.6 .8 à 1

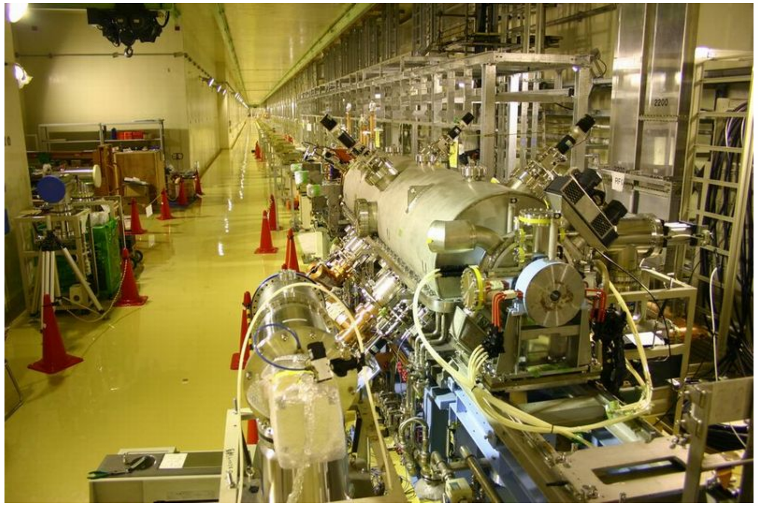
≈ 1

une "multi-purpose" Facility

J-PARC







- Phase 1 + Phase 2 = 189 billion Yen (= $1.89 billion if $1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

A second brand-new HPPA: SNS

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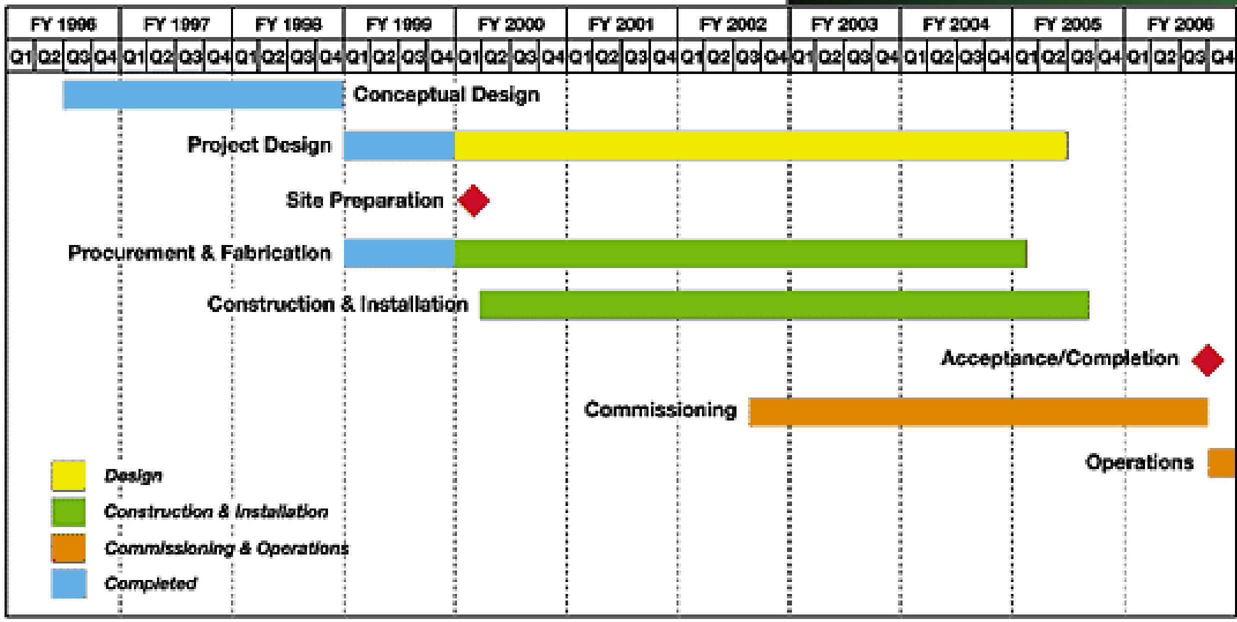
Institut National de Physique Nucléaire et de Physique des Particules

SNS at Oak-Ridge, beam since2006

SNS


161-kV Substation
Cooling Towers
Front End Building
Water Tower
Ring
Ring Service Building
Central Utilities Building
Linac
RTBT (Ring to Target Beam Transport)
Klystron Hall
CHL and SRF (Central Helium Liquefaction Building and Superconducting Radio Frequency Shop)
Dumps
HEBT (High Energy Beam Transport)
Target
Central Lab and Office Building


FY 1996
FY 1997
FY 1998
FY 1999
FY 2000
FY 2001
FY 2002
FY 2003
FY 2004
FY 2005
FY 2006
Q1 Q2 Q3 Q4
Conceptual Design
Project Design
Site Preparation
Procurement & Fabrication
Construction & Installation
Acceptance/Completion
Commissioning
Operations
Design
Construction & Installation
Commissioning & Operations
Completed

Choice of the Generic Accelerator Type

Main technical answers

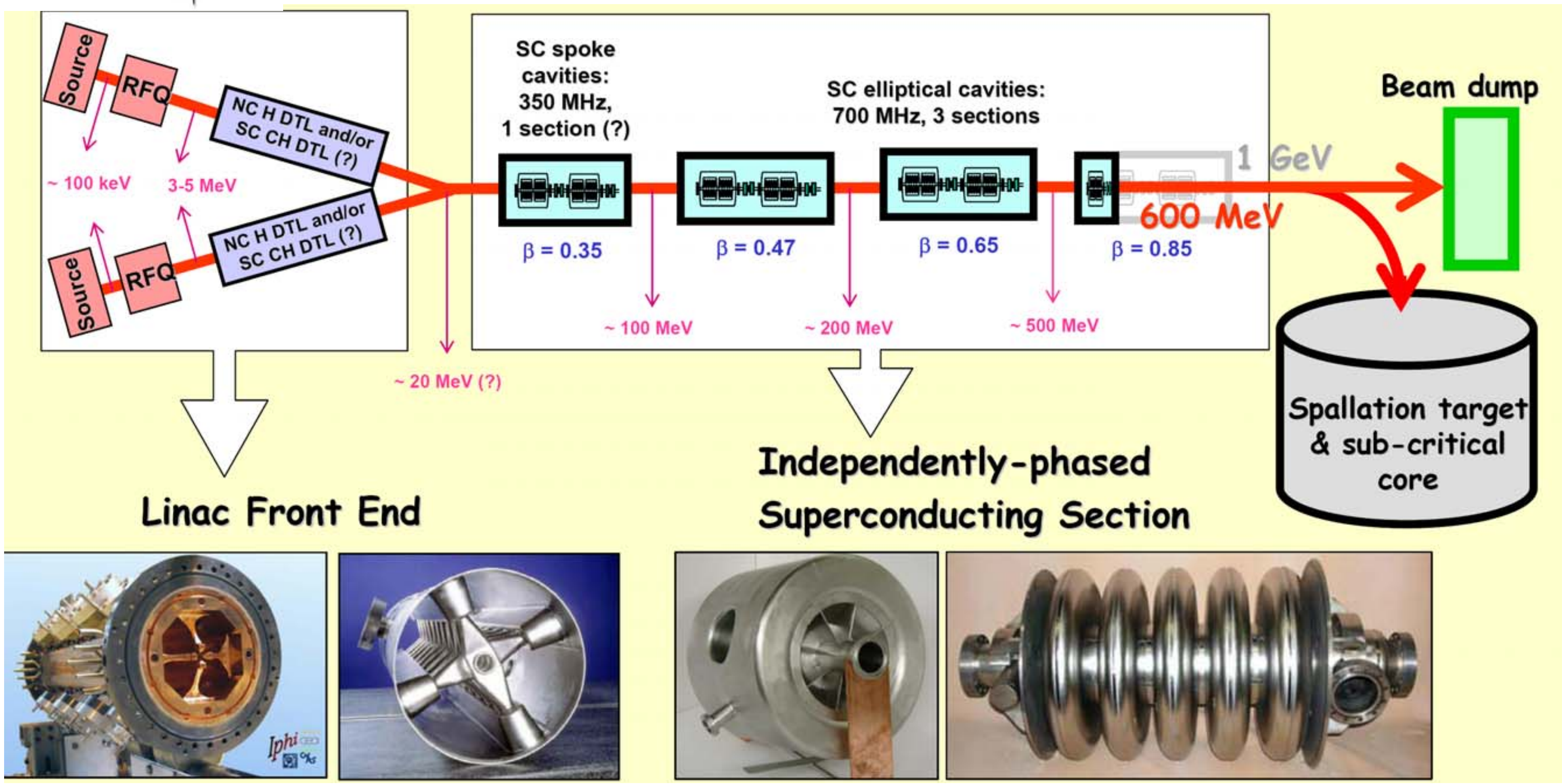
- Superconducting linac
  - No limitation in energy & in intensity
  - Highly modular and upgradeable (industrial transmuter)
  - Excellent potential for reliability (fault-tolerance)
  - High efficiency (optimized operation cost)
- Cyclotron
  - Attractive (construction) cost (?)
  - Required parameters at limits of feasibility ("dream machine")
  - Compact, but therefore not modular

In complete agreement with findings of the NEA report:

- **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
- **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

ADS accelerator reference scheme

PDS-XADS **Superconducting linac:** Highly modular and upgradeable (same concept for prototype & industrial scale) ; Excellent potential for reliability ; High efficiency (optimized operation cost)



Reliability Analysis

CONTRACT N°: FIKW-CT-2001-00179

FP5

ISSUE CERTIFICATE

PDS-XADS

Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/03/057 **Revision: 0**

Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators

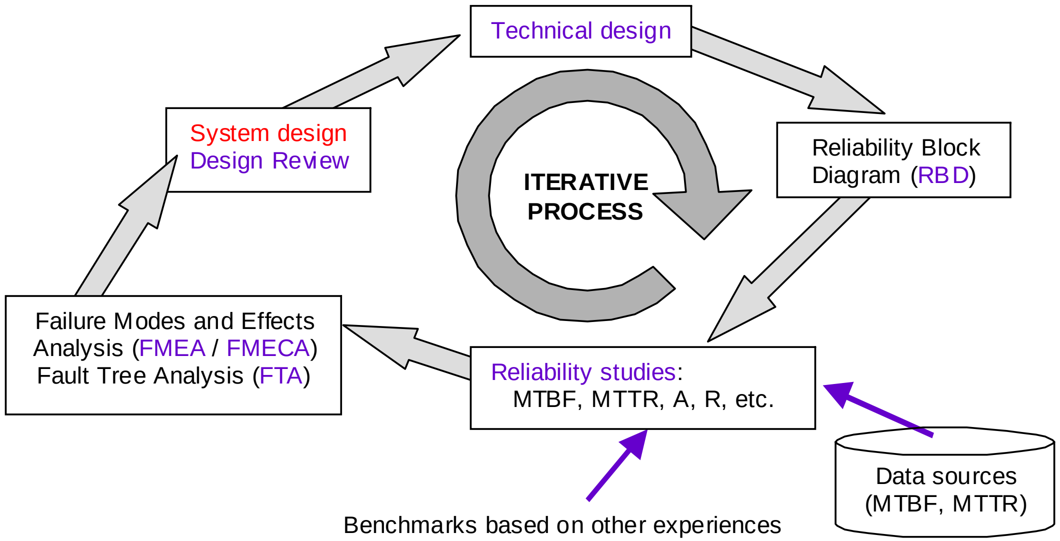
Dissemination level: *RE*
Issued by: *INFN*
Reference: INFN/TC_03/9 (July, 23rd, 2003)
Status: *Final*

Summary:

This document identifies the suitable design strategies that have been followed in order to meet the reliability and availability specifications for the XADS accelerator outlined in Deliverable 1. The document describes also how these strategies can be applied in the different components of the XADS accelerator design, and how design iterations can lead to reliability improvements. The Failure Mode and Effect Analysis (FMEA) methodology has been used on the suggested design for highlighting the reliability critical areas. Finally, a first rough cost estimation of the XADS accelerator is also provided.

23/07/2003	Paolo Pierini, INFN	Alex C. Mueller, CNRS	Bernard Carluec Framatome ANP SAS
	[signature]	[signature]	[signature]
DATE	RESPONSIBLE Name/Company Signature	WP LEADER Name/Company Signature	COORDINATOR Name/Company Signature

Assessments using the « Failure Modes and Effects Analysis » (FMEA) method



Reliability engineering is a discipline for estimating, predicting and controlling the probability of occurrence of system faults

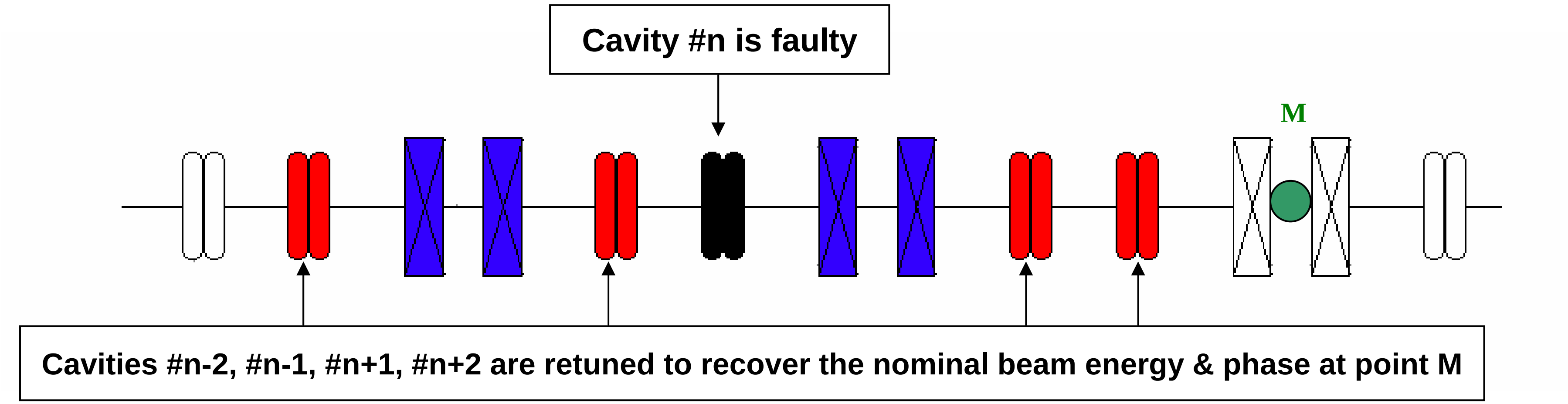
Optimisation of Accelerator Reliability for ADS

Need to have linac design that can handle the loss of one or several cavities

The modularity of our LINAC makes this possible because we have INDEPENDENTLY PHASED structures

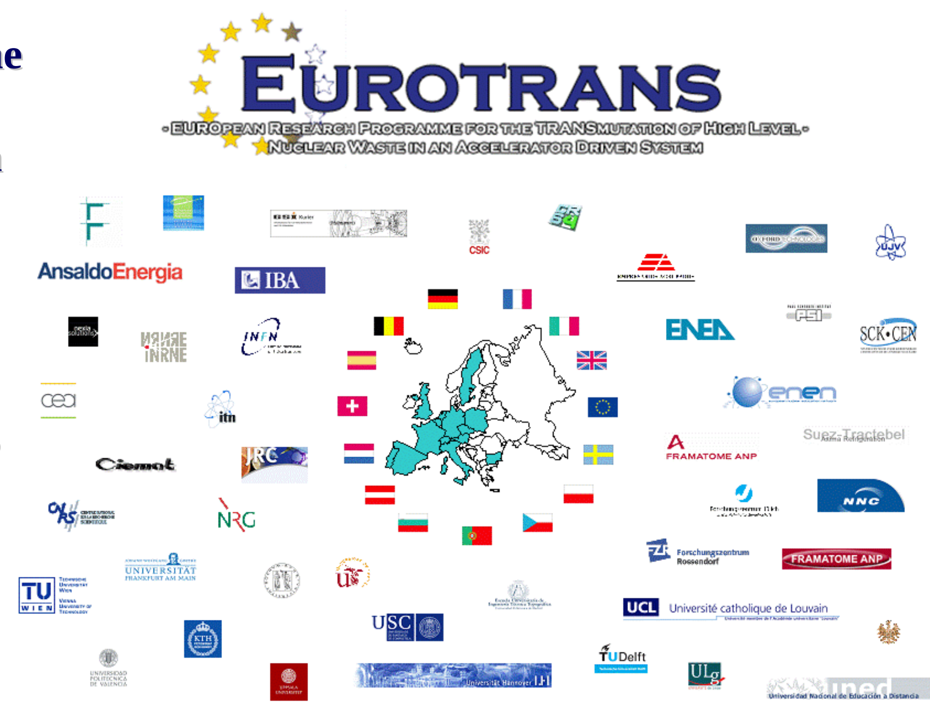
We need to find procedure that use the neighbouring cavities to compensate phase/energy beam offset

These procedures should then be integrated in RF control system



After "XADS" (FP5) EUROTRANS in FP7

- **EURopean research programme for the TRANSmutation of high level nuclear waste in an Accelerator Driven System**
- EU FP6 programme (2005-2009)
- 31 research agencies & industries, 16 universities
- Expands the EU FP5 project PDS-XADS (2001-2004)
- 5 Domains (DM1=Design, ...)



<u>**Main GOAL of the EUROTRANS programme**</u>

- Advanced design of a 50-100 MWth eXperimental facility demonstrating the technical feasibility of Transmutation on an ADS **(XT-ADS, short-term realisation)**
- Generic conceptual design (several 100 MWth) of a European Facility for Industrial Transmutation **(EFIT, long-term realisation)**

European Transmutation Demonstration

CNRS IN2P3 Institut National de Physique Nucléaire et de Physique des Particules

1. XT-ADS (ADS prototype)

- Goals:
  - **Demonstrate the concept** (coupling between accelerator, spallation target & reactor),
  - **Demonstrate the transmutation**
  - **Provide an irradiation facility** and an EFIT test bench
- Features:
  - 50-100 MWth power
  - Keff around 0.95
  - 600 MeV, 2.5 mA proton beam (or 350 MeV, 5 mA)
  - Conventional MOX fuel
  - Lead-Bismuth Eutectic coolant

2. EFIT (Industrial Transmuter)

- Goals:
  - Maximise the transmutation efficiency
  - Easiness of operation and maintenance
  - High level of availability for a cost-effective transmutation
- Features:
  - Several 100 MWth power
  - Keff around 0.97
  - 800 MeV, 20 mA proton beam
  - Minor Actinide fuel
  - Lead coolant (gas as back-up solution)

Accelerator main specifications

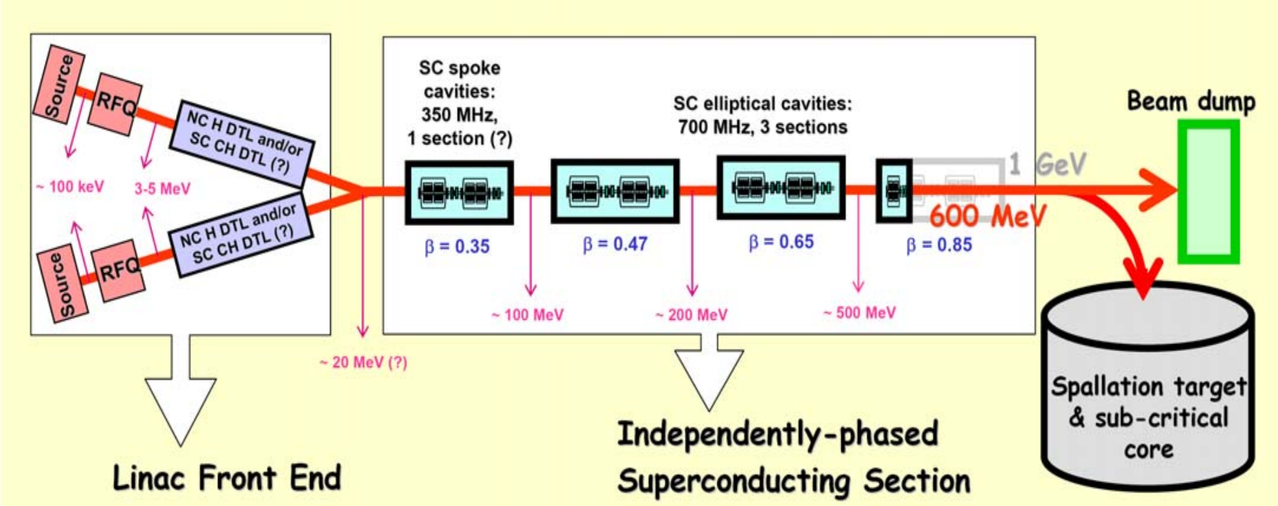
High-power proton CW beams

Table 1 – XT-ADS and EFIT proton beam general specifications

	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %	
Beam footprint on target	Circular ∅ 5 to 10 cm, "donut-shaped"	An area of up to 100 cm² must be "paint-able" with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 µs zero-current holes every 10^{-3} to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)	

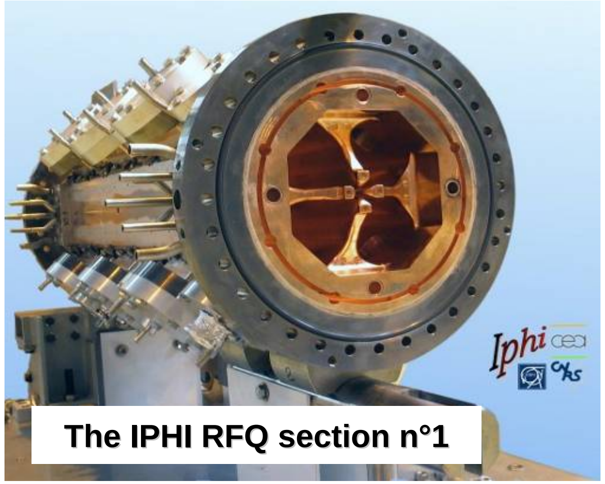
Extrememely high reliability is required !!!

Reliability-oriented accelerator tasks



- **Task n°1 :** Experimental evaluation of the **proton injector** reliability
- **Task n°2 :** Assessment of the reliability performances of the **intermediate-energy** acceleration components
- **Task n°3 :** Qualification of the reliability performances of a **high-energy cryomodule** at full power and nominal temperature
- **Task n°4 :** Design of a prototypical **RF control system** for fault-tolerant operation of the linear accelerator
- **Task n°5 :** Overall coherence of the **accelerator design**, final reliability analysis, cost estimation for XT-ADS & EFIT

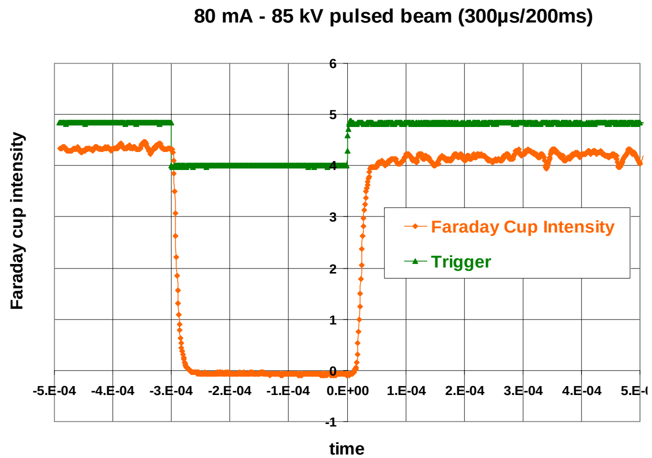
Task 1 – IPHI injector reliability test



The IPHI RFQ section n°1

The IPHI final beam line

- SILHI Source operational (100 mA, 95 kV)
- Fabrication / installation of RFQ & beam line in progress
- Successful tests of short beam holes production for sub-criticality monitoring (25us fall & rise time)

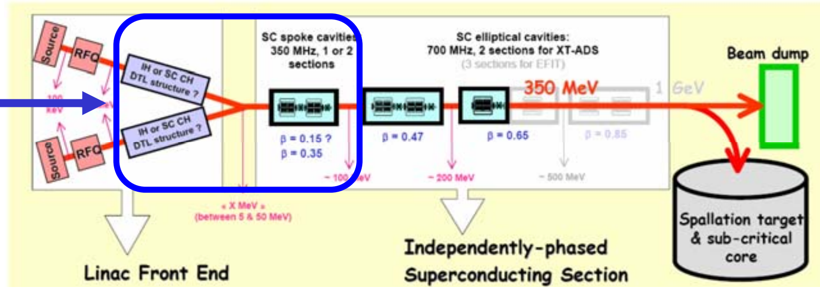


Final PURPOSE => Real scale long reliability test run

The 3 MeV beam will be continuously operated over a period of 2 months with beam intensity 20-40 mA

Task 2 - Intermediate-energy

Intermediate Energy Section
(3/5 MeV -> 100 MeV)



2 main types of structures are evaluated

- **Multi-gap H structures** (front end)
- **Superconducting spoke cavities** (independently-phased linac)

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Task 3 – High-energy Cryomodule

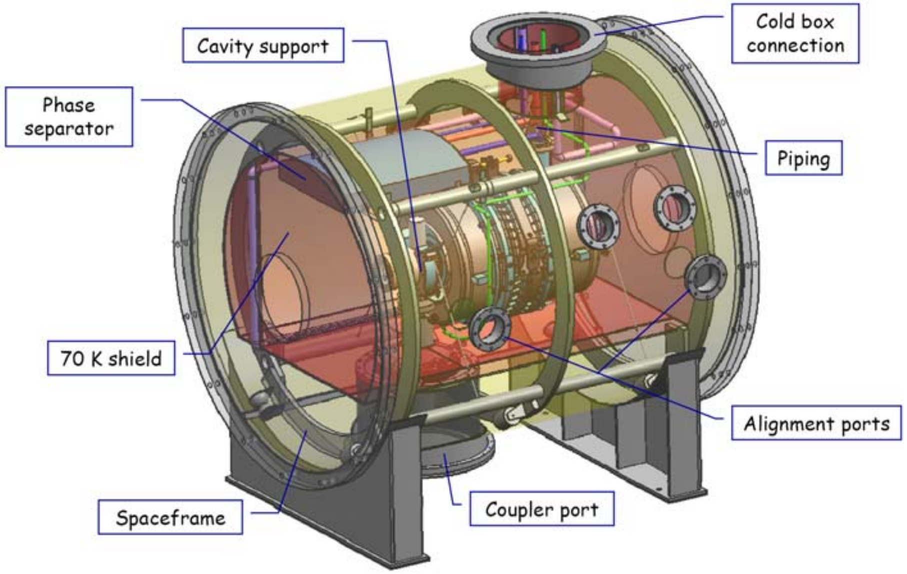
Design, fabrication & test of an elliptical module at nominal power & temperature

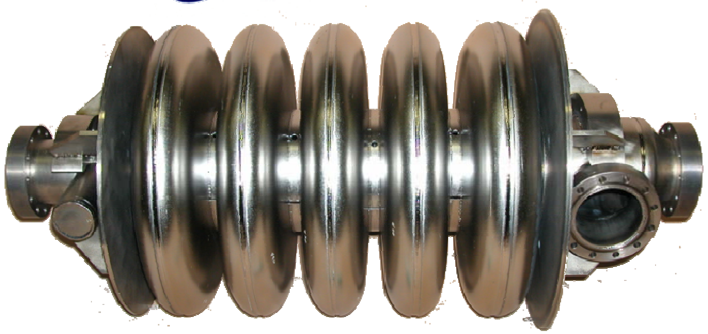
- β =0.47 prototype constructed and tested

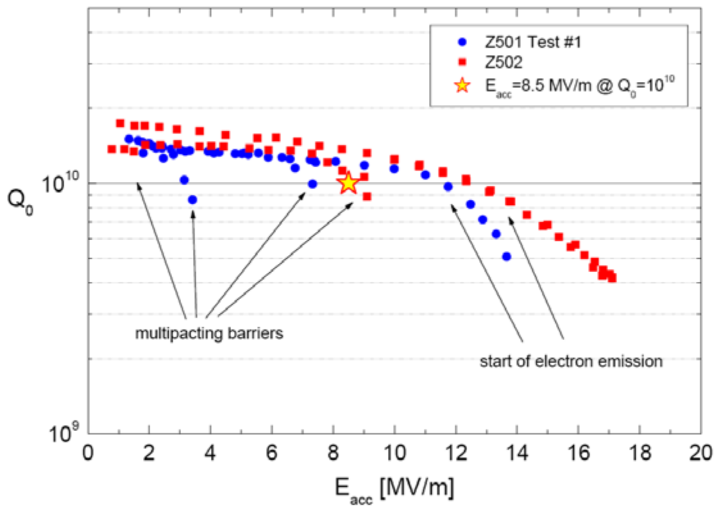
- Vessel & valve box nearly ready to be ordered

- CW RF power coupler under final design

- 700 MHz RF 80 kW power source received



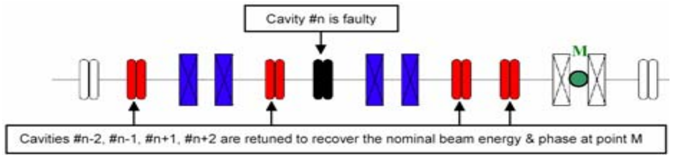




Task 4 – RF Control System

<u>**Fault-tolerance = ability to loose a RF cavity (or Q-pole) without loosing the beam**</u>

- Based on a fast local **compensation method,** possible thanks to the independently-phased linac



- Two **fast failure recovery scenarios (<< 1 sec)** have been identified & checked on the beam dynamics point of view, both based on:
  - Fast fault detection
  - Fast update and tracking of the field/phase set-points (preset)
  - Adequate management of the tuner of the failed cavity
- Requires up to 30% **margins** on RF fields and powers
- **Requires the use of <u>digital LLRF control systems</u>**
  - Heavy R&D on-going on this topic

FPGA based DIGITAL SYSTEM

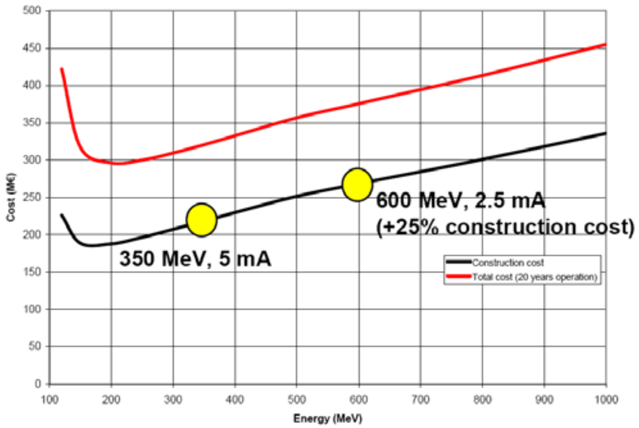
Note -> Fault recovery system in real operation at the SNS SC linac (US) (global compensation method, "high" energies, "slow" retuning)

J-L. BIARROTTE, ICENES 2007, 04-08 June 2007, Istanbul, Turkey.

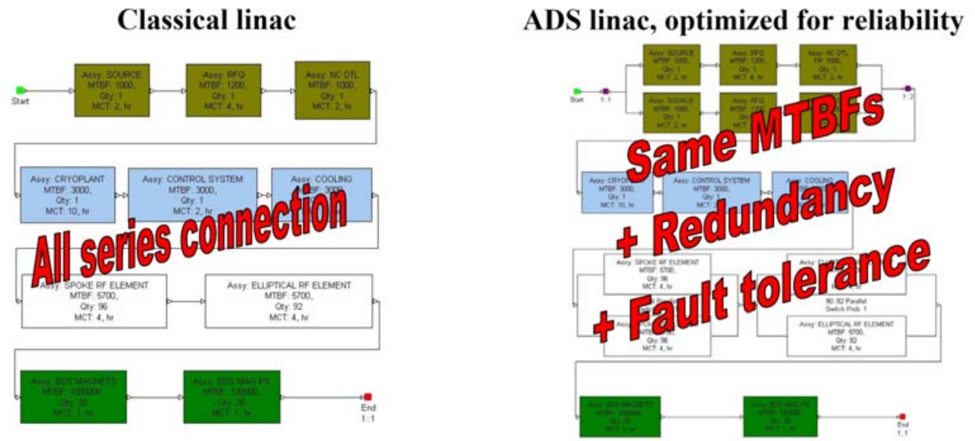
Task 5a – Accelerator conceptual design

GOAL => **Reach an "as much as possible" frozen design with assessed reliability figure and costing in 2009**

XT-ADS cost parametric study



Preliminary reliability analysis

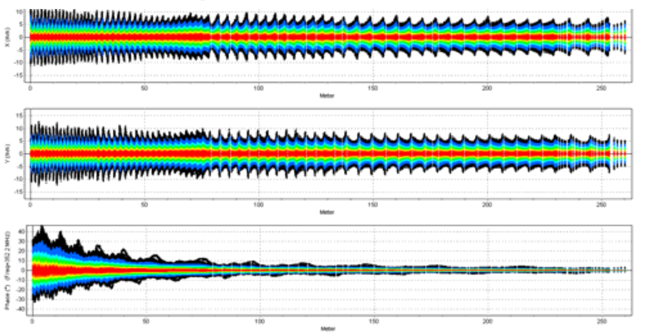


Classical linac	
System MTBF	31.19 hours
Nb of failures (3 months)	**70.23**
Steady State Availability	86.6 %

ADS linac, optimized for reliability	
System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

Preliminary reliability estimations by P. Pierini, INFN

Beam dynamics simulations



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INFN

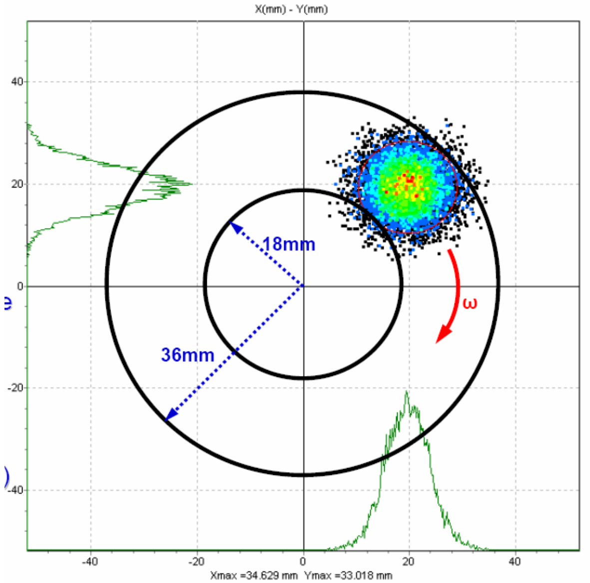
=> **The "less than a few beam trips per year" goal is REACHABLE**

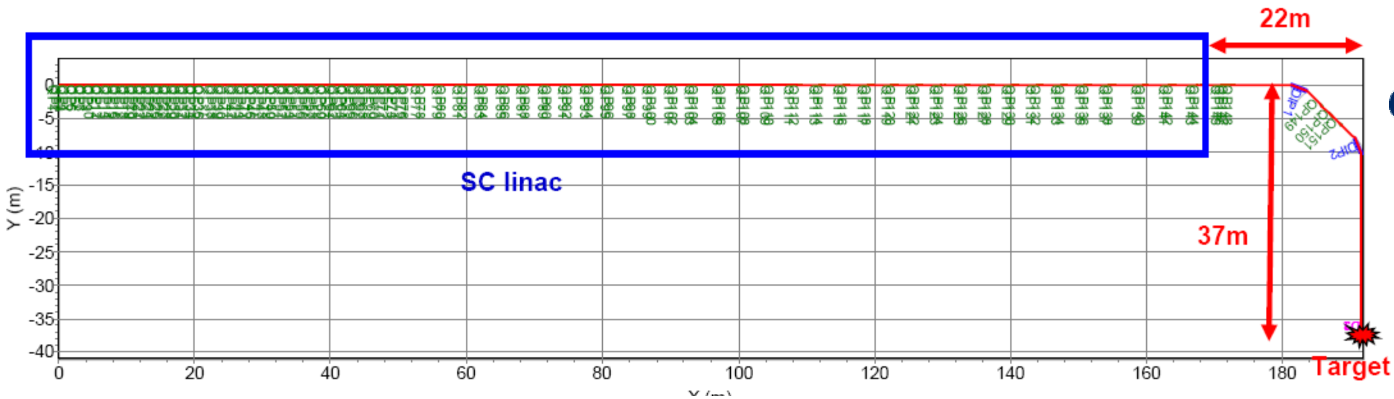
Task 5b – Interface with the reactor (or user!)

- **<u>Design of the final beam transport line with shielding</u>**
  - Connects the linac to the LBE spallation target
  - Guarantees the position of the beam spot and ensures that only particles of nominal energy are delivered (doubly-achromatic line)
  - Guarantees the shape and required distribution at the target (redundant beam scanning)

+ Analysis of beam transients effect on fuel and target

+ Investigations on Control/Command general philosophy





AnsaldoNucleare
Una Società Finmeccanica

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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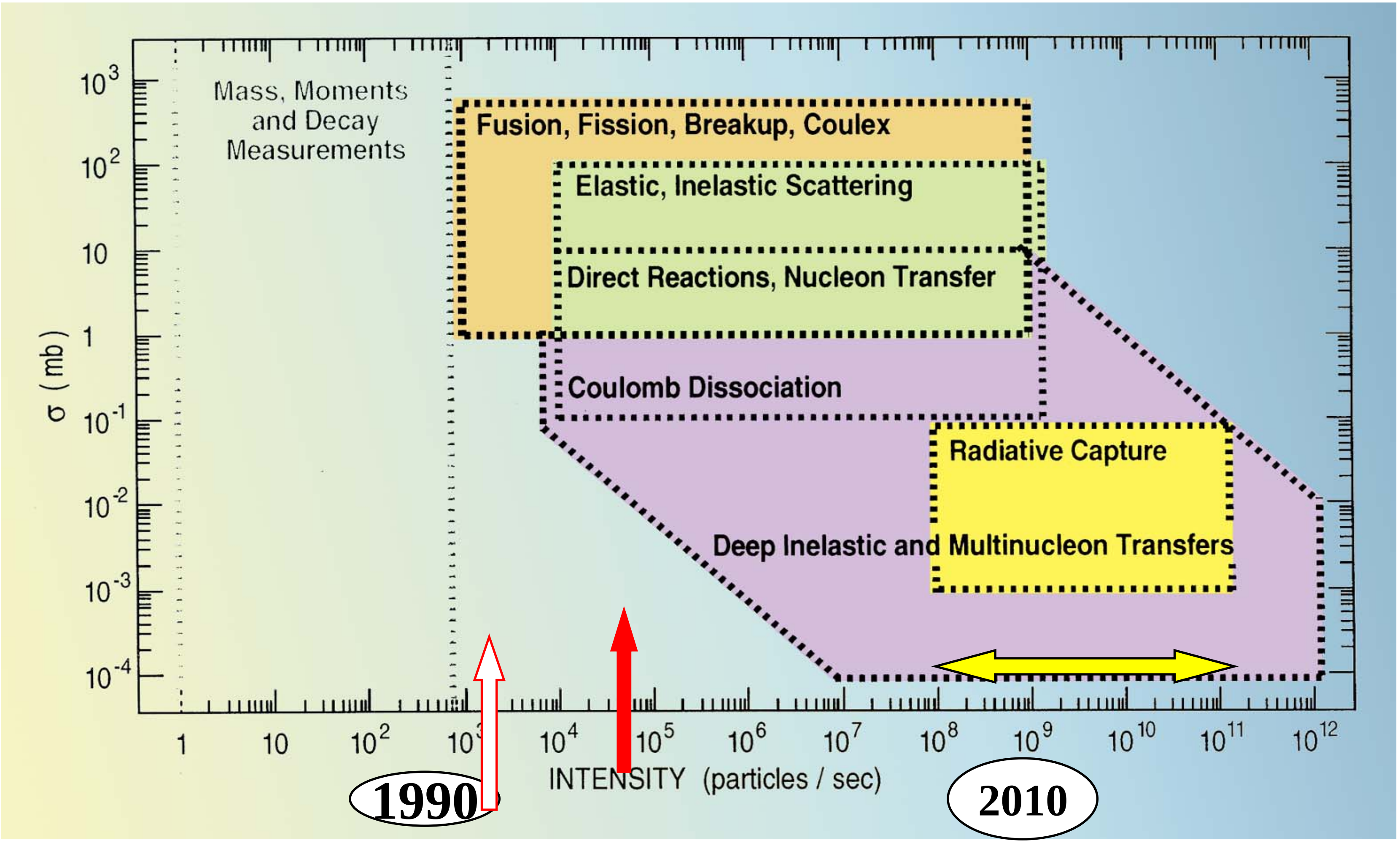
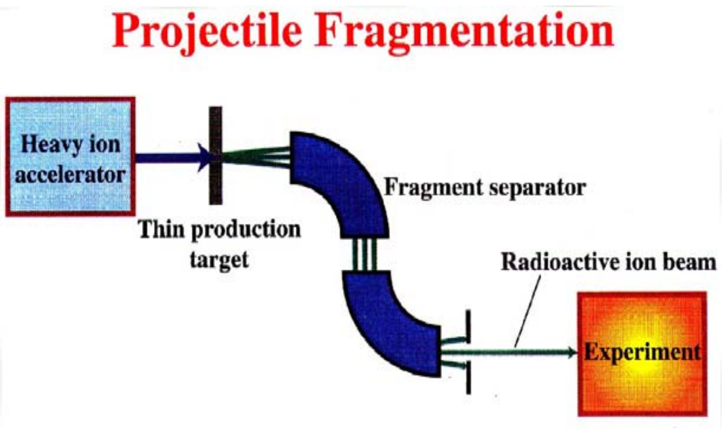
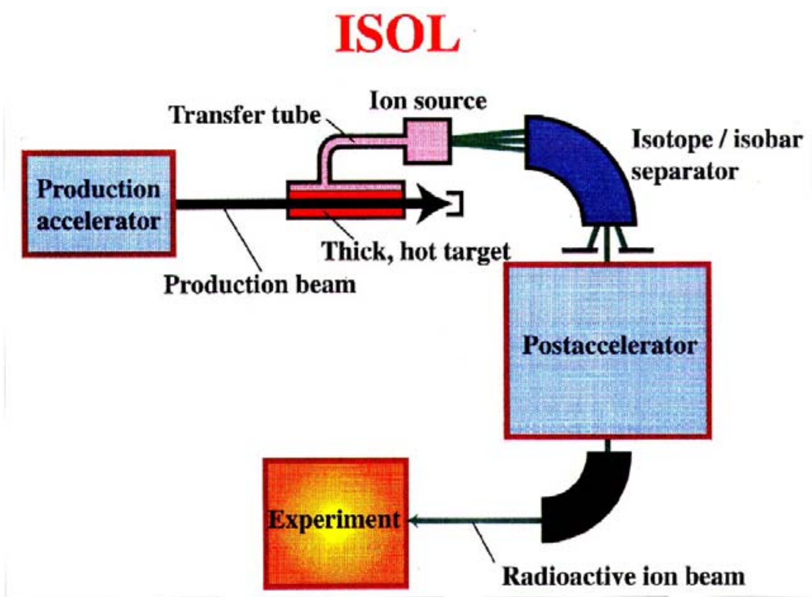
Physics with Radioactive Ion Beams: Reactions & Rates



Conclusions of the NuPECC Working group on the "Next Generation European Radioactive Ion Beam Facilities in Europe" (April 2000)

Next generation of RIB facilities should aim at intensities 1000 times higher than in the facilities presently running or at the commissioning stage. Two truly complementary facilities based respectively on the « In flight and Isol » methods are needed to cover the foreseen physics issues. And they should be second to none world-wide





Figures of Merit (in first order approximation)

Transparency borrowed from P. van Duppen

Secondary beam intensity:

$I_{secondary} = \sigma_{production} N_{target} I_{beam}$
$\times\ \varepsilon_{release\ -\ transport}$
$\times\ \varepsilon_{ionization}$
$\times\ \varepsilon_{transport\ -\ storage\ -\ post\text{-}acceleration}$

Intensity

Event rate:

$I_{counts}(reaction) = I_{secondary}\ \eta_{branching}\ \sigma_{reaction}\ N_{secondary\ target}$
$\times\ \varepsilon_{spectrometer}$
$\times\ \varepsilon_{detector}$

$I_{counts}(decay) = I_{secondary}\ \eta_{branching}$
$\times\ \varepsilon_{detector}$

Sensitivity

Pureness of the secondary beam: $I_{secondary}/I_{total}$

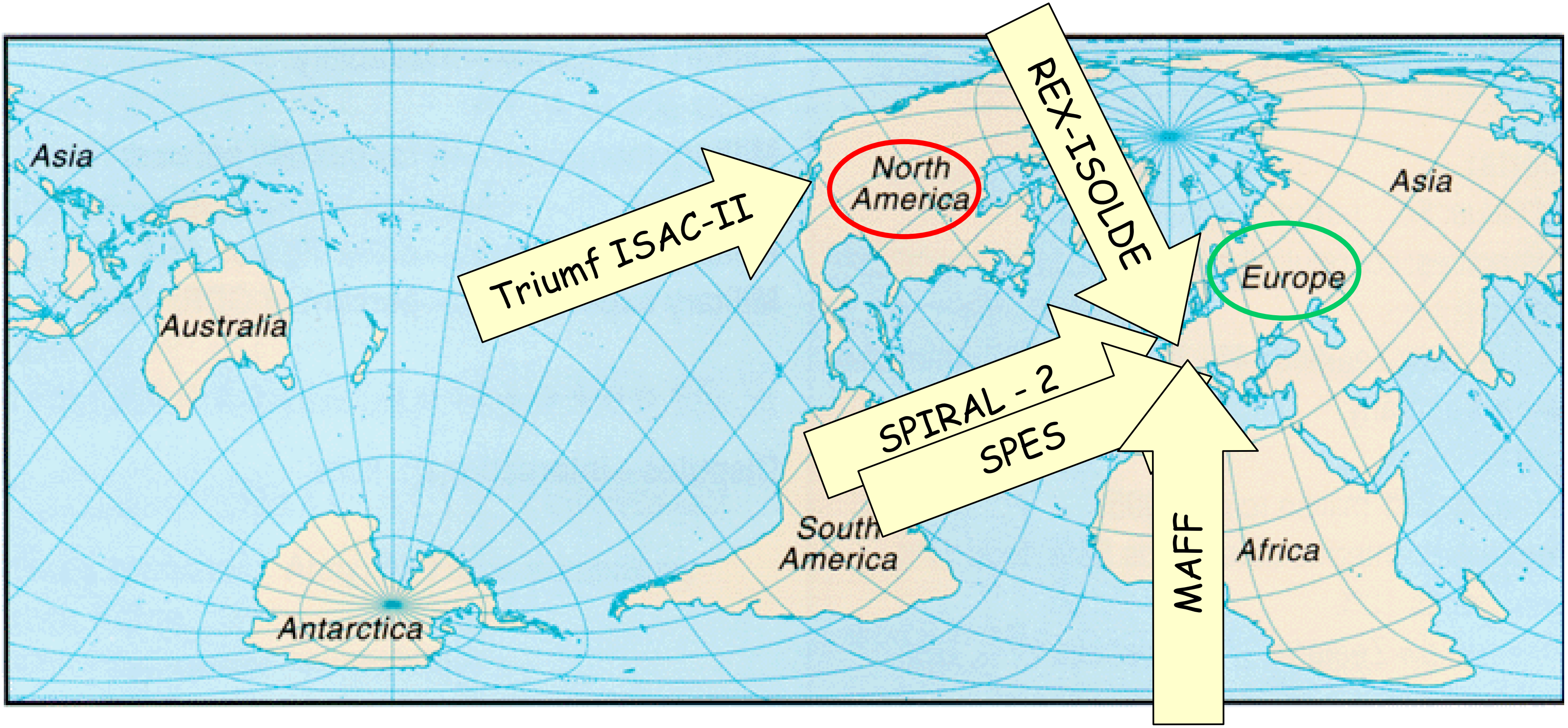
Selectivity

Peak to background: $R_{resolving\ power}$
(suppression of background, identification of events)

FAIR : The 2nd generation in-flight facility

again from
Piet van Duppen

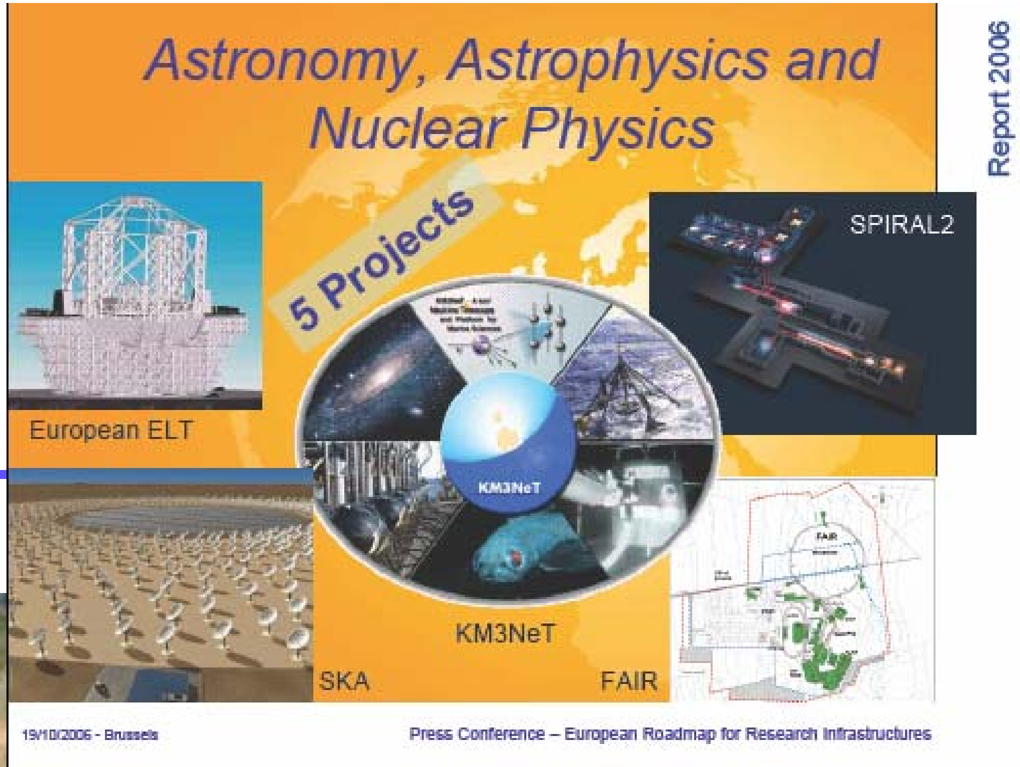
On the road towards EURISOL: upgrades and new comers (ISOL-based)

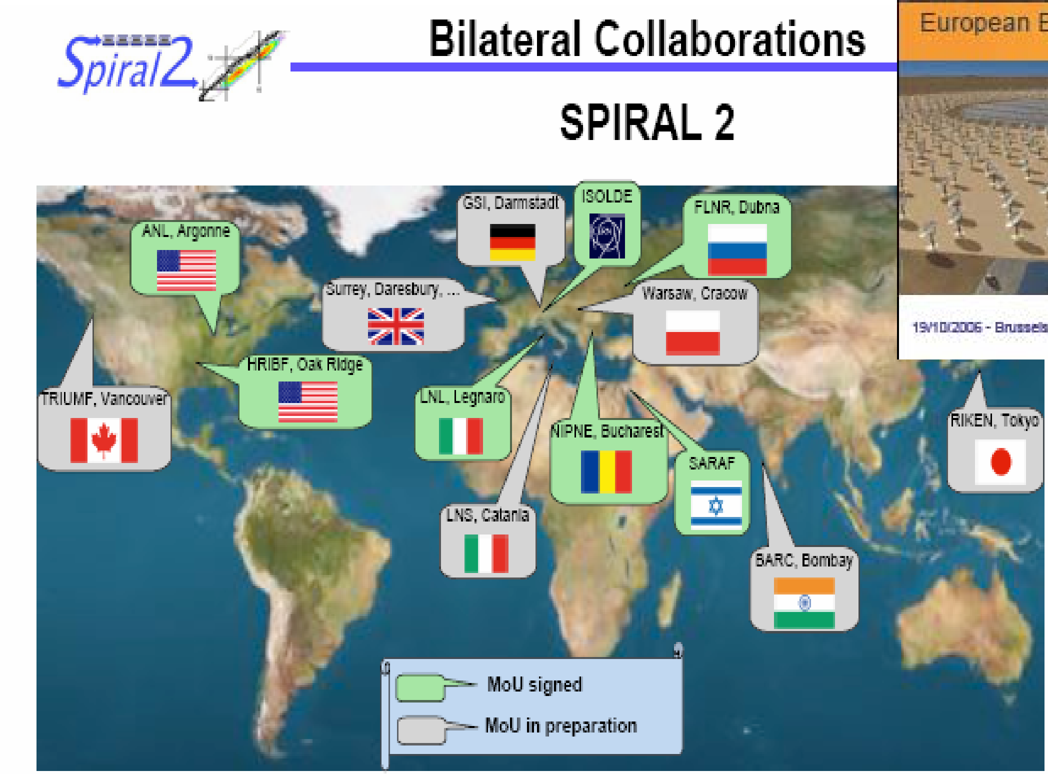


EURISOL

European Separator On-Line
Radioactive Nuclear Beam Facility

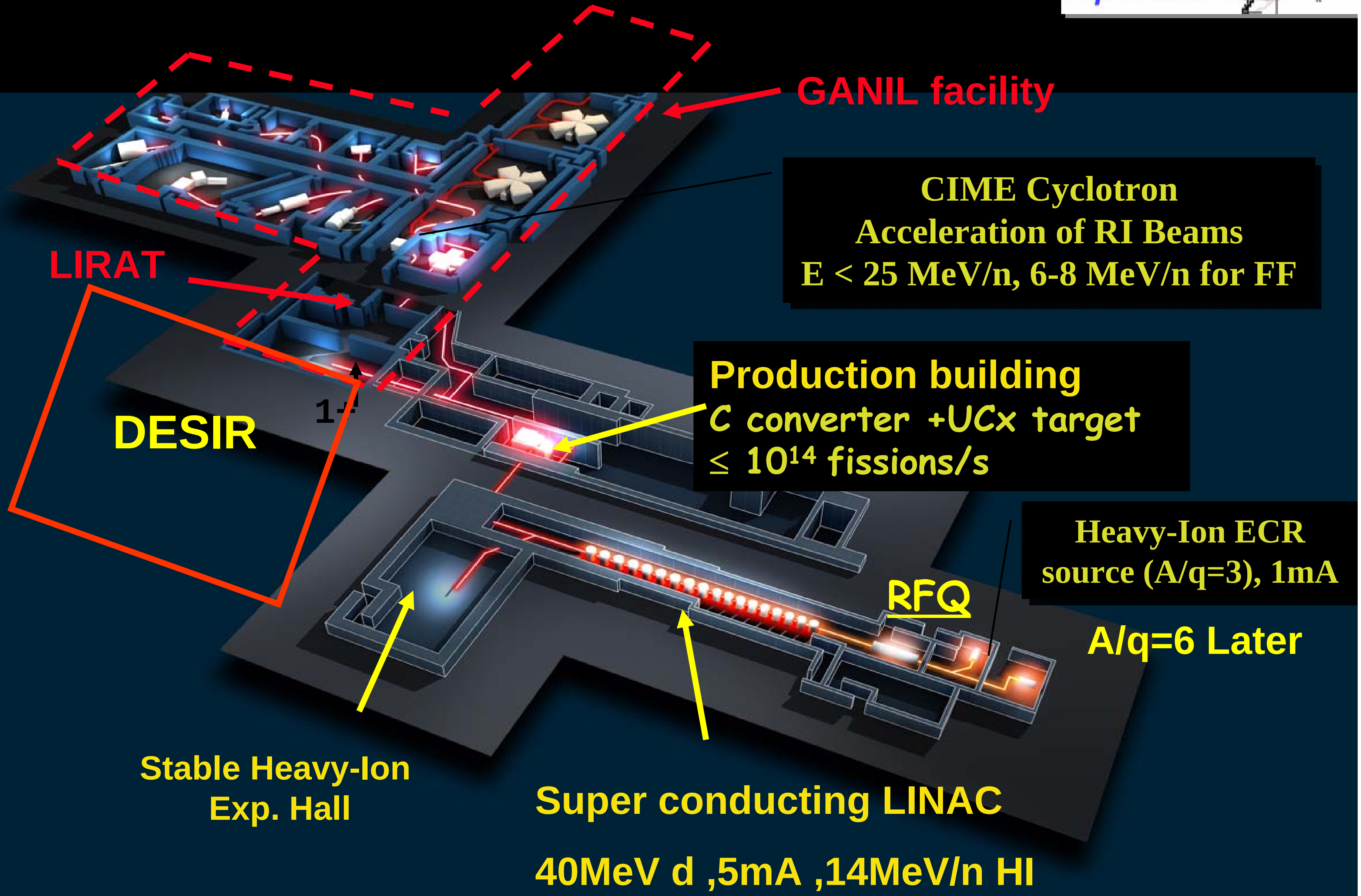
FAIR & SPIRAL 2 on the ESFRI list



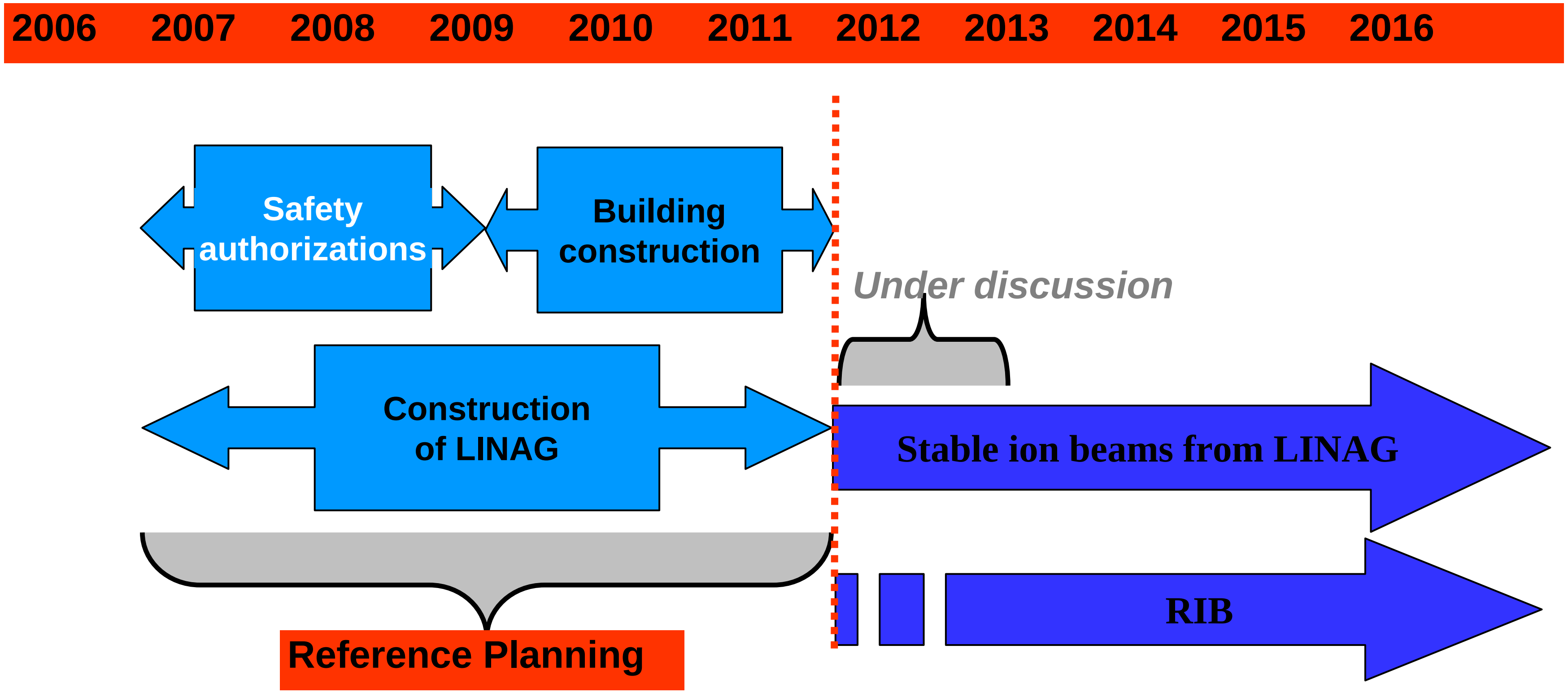


Brussels, 19 October 2006
European Research Infrastructures –
The ESFRI roadmap identifies 35 large-scale infrastructure projects

SPIRAL 2@GANIL – Next generation of ISOL Facility

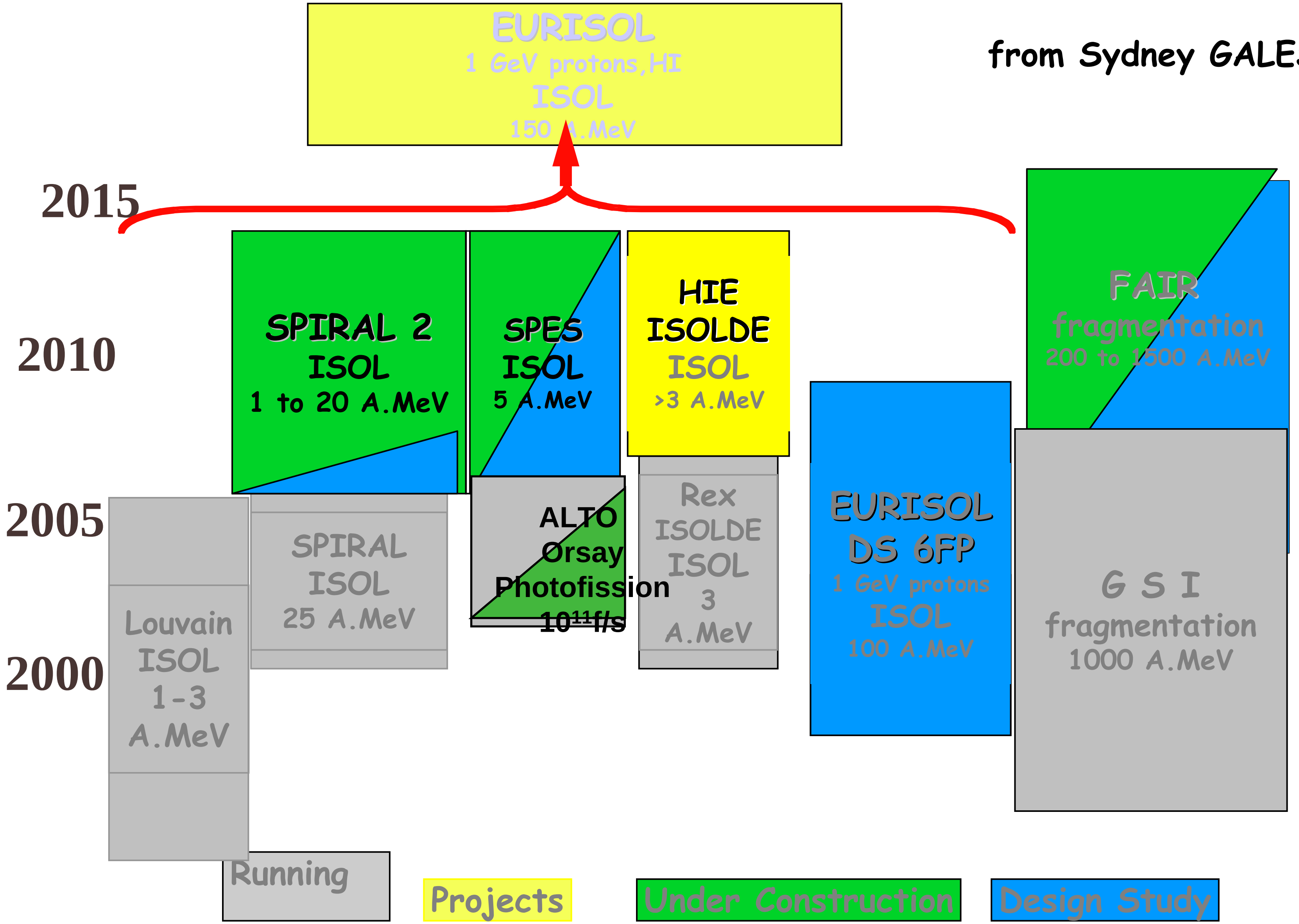


SPIRAL 2 Schedule

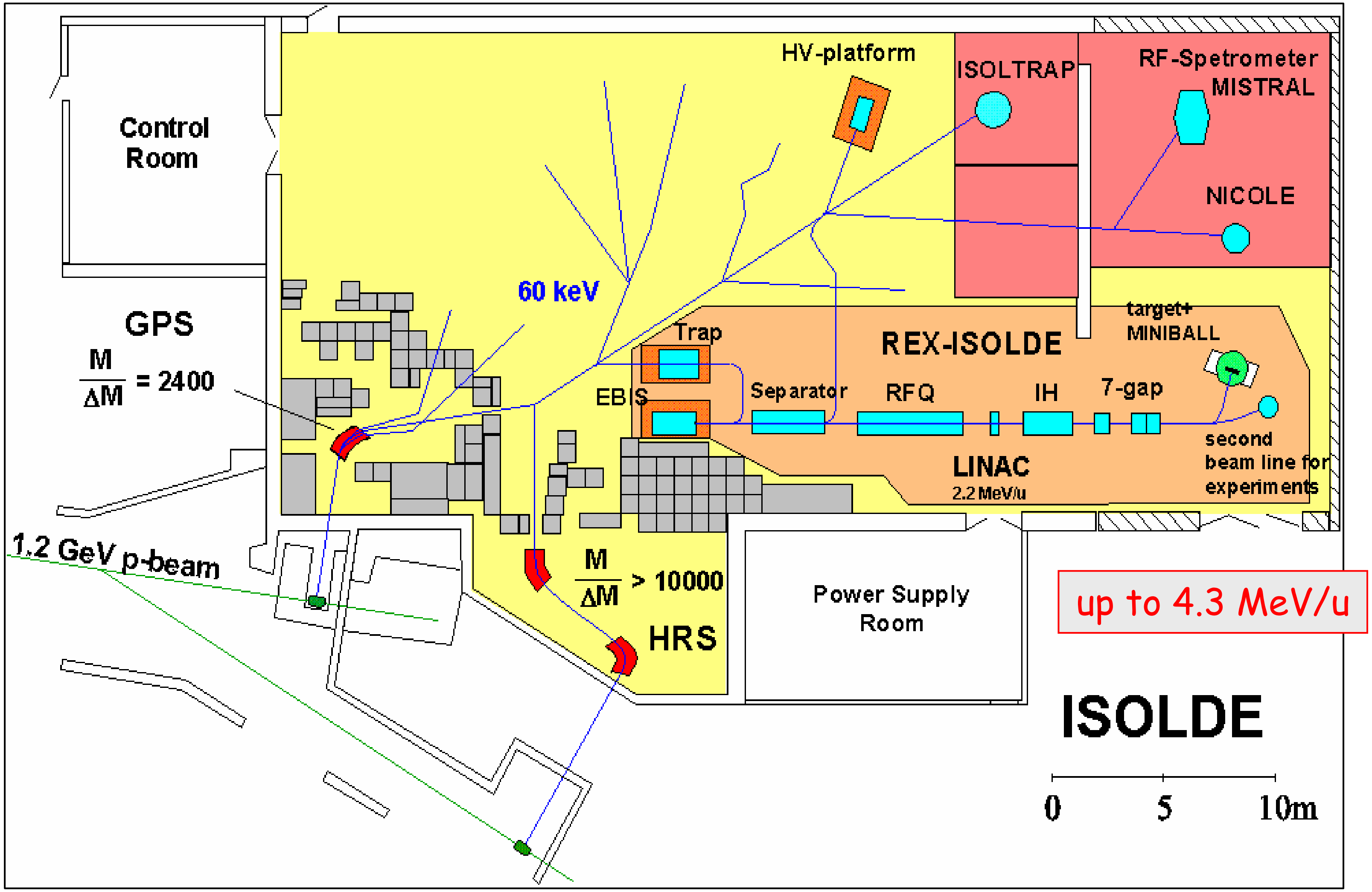


European RNB Facilities - Road Map

from Sydney GALES



REX-ISOLDE at CERN



Last, but not least:

Do not forget the phantastic need for Nuclear Education with hands-on experience !

and thank you for your attention